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Investigation of White Light Emission Observed during Damage in the Bulk of DKDP Crystals

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Abstract: We have investigated the flash of light that accompanies laser damage using time-resolved spectroscopy. Damage events were initiated in the bulk of DKDP and fused silica with 355-nm, 3-ns pulsed radiation. Spectra from the accompanying flash were recorded in the 200-500 nm wavelength range with 10-ns temporal resolution. Ten ns following damage initiation, the spectra were found to be roughly blackbody with temperatures on the order of 5000 - 7000 K. The observed temperatures and cooling rates can be related to the size and electron density of the plasma "fireball" that initiates the damage event.
OCIS codes: (300.2140) Spectroscopy, Emission (140.3330) Laser damage

1. Introduction

The observed laser damage threshold in optical materials is significantly less than the theoretical intrinsic value. In fused silica, for 350-nm light, it has been estimated that the onset of avalanche breakdown should be on the order of 150 GW/cm^2 [1]. For the 3-ns pulses used in this study, this corresponds to 450 J/cm^2; which is 40 to 50 times the experimentally observed values. This discrepancy is generally attributed to the presence of defects, intrinsic or extrinsic, contained within nominally transparent materials [2,3].

When laser damage occurs, plasma is formed at the sites of these defects and rapidly expands, absorbing large amounts of energy during the laser pulse [4,5]. The high energy density produces a micro-explosion, damaging the material. Shockwave propagation induces mechanical failure and material modification. This is followed on a slower time scale by melting and further material modification caused by temperature increase [6,7]. The white light emissions, which accompany these processes, contain crucial information concerning the mechanisms responsible for the damage. In this work, we report that the emission spectrum of fused silica is blackbody in nature as early as 10 ns after the termination of the laser pulse and that the ionized region can approach temperatures of 7000 K.

2. Experimental

Fused silica (SiO_2) and DKDP Crystals samples at room temperature were irradiated with 355-nm 3-ns pulse radiation focused in the bulk of the materials with a spot determined by a knife-edge measurement to be approximately 30 μm in size. The pump beam is brought in through a small turning mirror and focused by an off-axis parabolic mirror into the sample. A schematic representation of the apparatus may be seen in figure 1. The short focal length of the mirror eliminated the possibility of surface damage and allowed the study of the bulk properties of the materials in question.

The same mirror collects the emission from the damage area with an f-number of unity. The collimated refection is transported by reflective optics to an f-4 mirror and focused into a 200-μm spectrometer slit. The 50-μm collection region from this geometry closely matches the spot size of the damaging beam and thus reduces extraneous signal from sources such as bulk fluorescence. By using only reflective optics we prevent excessive loss in UV that would be experienced with refractive optics. The response of the system and absorption of the sample was determined by use of calibrated light sources. The data were reduced by removing background and instrument response. Commercial software was then used to fit the spectra to a modified Planckian distribution:

$$I(\lambda) = C_1 + C_2\lambda^{-5}(e^{0.144/T\lambda} - 1)^{-1} \quad (1)$$

where C_1, C_2 and T are fitting parameters. Fitting with a pure Planckian (C_1=0) gives a slightly worse fit, but yields temperatures that differ by no more than 10%. This discrepancy does not effect the conclusions of this work.

A selection of data and the extracted temperatures are displayed in figures 2a and 2b. Additional fused silica data will be discussed in a future work [8].
A break in the data (individual points) can be seen from 325 nm to 425 nm. This brake is due to a physical obstruction used to protect the ICCD from the laser line. A holographic filter would notch a much narrower band, but would transmit poorly in the UV.

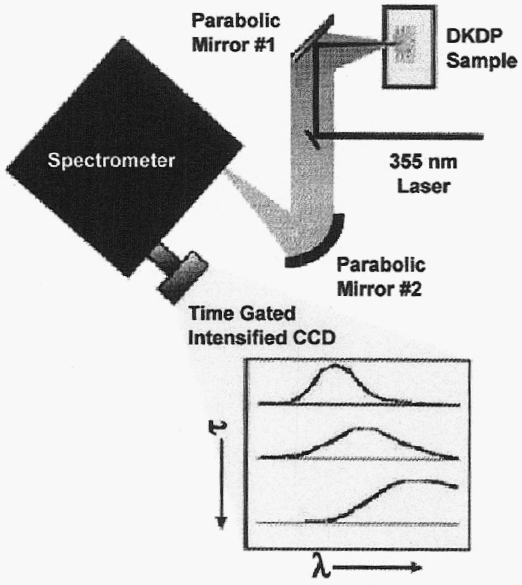

Fig. 1

The 355 nm light is reflected off a small turning mirror and then focused by an off-axis parabolic mirror in to the bulk of the sample. After damage is initiated, the same mirror collects and re-collimates the light which then passes the turning mirror with about 10% loss. A second mirror focuses the light into a spectrometer coupled with a time gated intensified CCD.

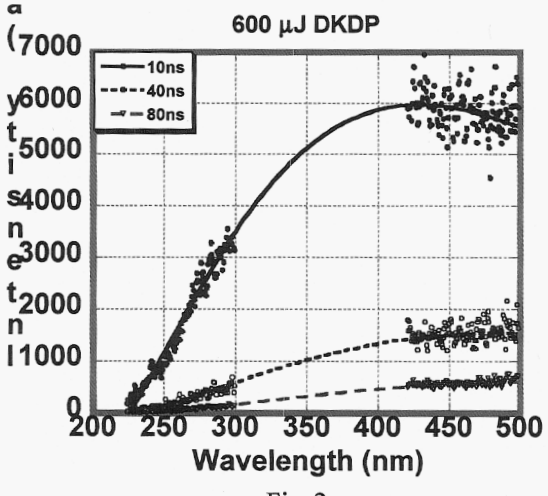

Fig. 2a

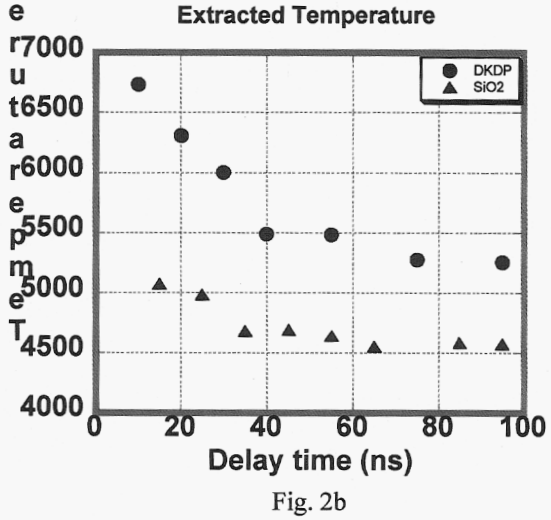

Fig. 2b

a)The individual points are the data collected from the ICCD from DKDP for 10, 40, and 80 ns after the laser pulse. The curves through the data are the fits generated by equation 1. Gaps in the spectra are the result of an obstruction blocking the laser line. b)Temperatures extracted form the fits of equitation 1. Despite the uncertainty in the temperature (~+/-200 K) the cooling of the ionized region can be seen as a function of delay time after the laser pulse has terminated.

3. Discussion

In this work we have demonstrated that the emissions accompanying laser damage in fused silica and DKDP are blackbody in nature at times ranging from 10 ns to 100 ns after the laser pulse. The elevated temperatures observed indicate that a substantial amount of energy was absorbed from the laser fields. Because the surrounding material confines the plasma, its density must be essentially unchanged from the solid state. From the equation of state for fused silica, the pressure at the temperatures observed must be on the order of 150 kbars [9]. This yields an energy density on the order of 10 kJ/cm^3. We can estimate from the cooling rate that the ionized region is on the order of 5 μm in size [10].

For a fireball of 5 μm in size the energy density corresponds to absorption of roughly 15 μJ, or ~2% of the laser pulse. This level of absorption can occur only if the electron density is on the order of the critical density (10^{22} cm^{-3}) so that at least a small region is opaque to the laser radiation. The equilibrium electron density of 10^{17} cm^{-3} predicted by the Saha formula (electrons promoted across the band gap thermally) for the temperatures observed is several orders of magnitude too small for effective absorption to occur [4,9,11]. For this reason the electrons cannot be purely thermal in origin. The majority of free electrons must then be produced by impact ionization and electron avalanche.

4. Conclusion

Time resolved emission spectra observed during laser damage at time greater than 10 ns is found to be blackbody in nature. By fitting the emission spectra we are able to determine the temperature of the plasma fireball that produced the damage. The blackbody nature and high temperature of the ionized region indicates electron densities near or above the critical density are reached during laser irradiation and persist for tens of nanoseconds.

5. Acknowledgement

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